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# Lineage tracing methods to study kidney injury and regeneration, their limitations and advantages

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**Running title:** *Lineage tracing strategies for kidney regeneration*

## 36    **Abstract**

37    Lineage tracing strategies is proving to be a powerful approach for tracking cells *in vivo*, and is transforming  
38    our understanding of the cell fate changes that underlie kidney pathophysiology. The technological advances  
39    in lineage tracing approaches is permitting novel spatial, temporal and kinetic resolutions into mechanisms  
40    responsible for tissue renewal and repair. In particular, lineage tracing has been used to investigate the  
41    possible role of stem/progenitor cells in kidney development, homeostasis and regeneration. Recently, the  
42    production of novel murine models where individual cells are tagged, assist in clarification of mechanisms of  
43    kidney regeneration and new answers to old questions are gradually being unraveled. The complexity of  
44    these genetically engineered systems requires careful analysis and interpretation. Caution must be paid  
45    particularly on the type of promoter, switch and reporter used, as well as on the induction times that are best  
46    to study the pre-specified end points. Here, we focus on the main points that need to be considered to  
47    interpret results obtained with lineage tracing, as well as on novel techniques that are becoming available,  
48    with a particular emphasis on their use for studying putative renal progenitors and the mechanisms of kidney  
49    regeneration.

## 50    **Keypoints**

- 51        • The principle of lineage tracing is based on marking a single cell in such a way that the mark is  
52        transmitted to the cell's progeny.
- 53        • Lineage tracing can provide information about the number of progeny of the founder cell, their  
54        location, and their differentiation status.
- 55        • The critical points to consider for an appropriate evaluation of the data obtained with lineage tracing  
56        should be three: the promoter, the switch and the reporter.
- 57        • The choice of the promoter should be optimized based on the cell type that has to be studied.
- 58        • The best possible promoter is one that is specifically and selectively expressed by the cell type  
59        analysed.
- 60        • For any kind of promoter system used, the expression pattern has to be verified prior to the actual  
61        cell fate tracing experiments.
- 62        • If the cell type marked by the promoter is unknown, negative results never allow definitive  
63        conclusions.
- 64        • The switch is usually a drug-regulated form of the bacterial enzyme Cre recombinase, which  
65        activates the transgene to allow turning on and off transcription of the reporter in a time-dependent  
66        manner.

- 67 • The use of lines that express Cre constitutively is problematic for lineage tracing, because transient or  
68 later expression of the gene in other cells also likely induces *de novo* activation of Cre recombinase,  
69 potentially altering results interpretation.
- 70 • Critical points to evaluate the results are also represented by the induction times used to study the  
71 pre-specified end points.
- 72 • Fluorescent reporters allow not only qualitative evaluation of phenomena but also quantitation and  
73 live imaging through dual or multiphoton microscopy.
- 74 • Use of multicolor reporters allows evaluation of cell division and clonal analysis and provides the  
75 most accurate genealogical descriptions of stem/progenitor behaviors.

76

77

78 Until recently, the behavior of cells *in vivo* could only be inferred indirectly, and consequently the basis of  
79 tissue biology in the kidney was ill-defined. However, lineage tracing in transgenic mice is proving to be a  
80 powerful approach for tracking cell fate *in vivo*, and it is transforming our understanding of the cell fate  
81 changes that contribute to kidney injury and regeneration. Traditionally used in developmental biology,  
82 lineage tracing has become an essential tool also in stem cell research, because it provides information about  
83 how the cell behaves in the context of the intact tissue or organism.<sup>1-6</sup> Tracking cells in their native habitat  
84 has provided insight into how the balance of proliferation and differentiation is achieved to an extent never  
85 before envisaged and thus, lineage tracing is increasingly applied to solve numerous scientific problems. In  
86 particular, the use of lineage tracing has provided unprecedented levels of information about clonal dynamics  
87 and the organization of the stem cell compartment in postnatal tissues<sup>2-7</sup> and has recently been used to  
88 investigate the possible role of resident progenitor/stem cells in kidney development, homeostasis and  
89 regeneration.<sup>8-12</sup> However, the inherent complexity of genetic recombination techniques and the increasing  
90 number of possibilities associated with this technology makes the interpretation of the results of these studies  
91 accessible only to experts. Several excellent reviews were focused on the technical aspects of lineage  
92 tracing.<sup>13-15</sup> In this Review, we focus on the main points that need to be considered to interpret results  
93 obtained with lineage tracing, with a particular emphasis on their use for studying putative renal progenitors  
94 and the mechanisms of kidney regeneration.

96 **Lineage tracing: how it works** The basic concept of lineage tracing is simple, and is based on marking a  
97 single cell in such a way that the mark is transmitted to the cell's progeny. To this aim, expression of a  
98 reporter gene, such as the enzyme  $\beta$ -galactosidase or a fluorescent protein, is switched on in a subset of cells  
99 in a tissue<sup>16,17</sup>. If the labelled cells divide, they pass on the expression of the reporter to their daughter cells,  
100 and form clusters of labelled cells, providing information about the number of progeny of the founder cell,  
101 their location, and their differentiation status.

102 To conduct a lineage-tracing experiment a switch that is usually a drug-regulated form of the bacterial  
103 enzyme Cre recombinase, must be engineered into the mouse genome. This enzyme recognizes specific  
104 sequences, called *LoxP* sites<sup>16,17</sup>, that are not naturally found in the mouse genome, and are inserted only in

transgenic constructs used to create the transgenic line (**Fig.1**). Put simply, Cre recombinase excises the DNA between *LoxP* sites and rejoins the ends<sup>16</sup>(**Fig.1**). To control Cre activity have been developed modified promoters that are active only in specific cell populations and allow Cre transcription exclusively in a drug-sensitive fashion, thus leading to reporter expression.<sup>13-17</sup> Already from this summary, it is clear that the critical points to consider for an appropriate evaluation of the data should be three: the promoter, the switch and the reporter.

111

**The promoter** By enabling the tracking of cells and their progeny at any time point, lineage tracing is nowadays the most reliable technique to determine the stem or progenitor nature of a cell. However, the choice of the promoter is an essential determinant of results. For example, using lineage tracing Humphreys *et al* proved that tubular regeneration after acute kidney injury is totally derived from intrinsic epithelial cells.<sup>10</sup> Indeed, in this elegant study, the authors employed a mouse line in which the Six2 promoter directly derived the expression of the Cre recombinase fused to the GFP.<sup>10</sup> By crossing it with a Rosa26-LacZ or RFP reporter line they obtained the reporter heritable expression.<sup>10</sup> The authors were thus able to tag only Six2<sup>+</sup> renal epithelial precursors, which are present in the metanephric mesenchyme (MM) during the developmental period of active nephrogenesis.<sup>11</sup> All the MM-derived nephron epithelial cells including tubular cells, but no extra-tubular cells, were thus marked.<sup>10</sup> The paper demonstrated that, following an ischemic injury, no dilution of reporter-marked cells was present, and that surviving tubular cells were positive for both the reporter and the proliferation marker Ki67, indicating that all reparative epithelial cells originated from within the MM-derived nephron.<sup>10,18</sup> The use of this promoter for tracing, however, does not discriminate between terminally differentiated epithelial cells and putative intra-tubular progenitors, since cells from which tubular structures of the nephron are derived are marked at the time of embryogenesis. In addition, the use of a constitutive system cannot completely exclude upregulation of the label within the tubules after development (as discussed in detail below). Thus, to finally dissect the contribution of potential intratubular progenitors to tubular regeneration, lineage tracing strategies based on other promoters were proposed. Indeed, Kusaba *et al.*<sup>19</sup> used the sodium dependent inorganic phosphate transporter, SLC34a1, as a marker to trace terminally differentiated proximal tubular cells. Based on the fact that there is no dilution of

132 fate marker after injury and repair, the authors concluded that progenitors do not participate in tubular  
133 regeneration.<sup>19</sup> However, this work which relies on lineage tracing of a cell population unified by a cell  
134 marker, does not take into consideration the possibility that intrinsic renal progenitors may express  
135 differentiated tubular markers to some degree. Indeed, expression of differentiation markers by tissue  
136 resident progenitors was reported in several organs.<sup>20-24</sup> Thus, the choice of a tubule differentiation marker  
137 for the promoter may not allow excluding the existence of tubular-committed progenitors since they would  
138 be genetically tagged similarly to differentiated tubular cells.

139 Interestingly , several studies have proposed the existence in adult human kidney of a putative population of  
140 tubular progenitors characterized by co-expression of surface markers CD133 and CD24. These cells can co-  
141 express tubular markers although at lower levels than other differentiated tubular cells and localize within the  
142 tubule, scattered among differentiated tubular cells.<sup>25-27</sup> To trace these putative tubular progenitors, Berger *et al.*<sup>28</sup>,  
143 used a conditional mouse originally designed to reproduce the expression pattern of the endogenous  
144 podocalyxin gene within podocytes.<sup>8</sup> In this mouse, transgene expression was unexpectedly detected within  
145 parietal epithelial cells of the Bowman's capsule but not within podocytes.<sup>8</sup> This allowed tracing the  
146 migration of parietal epithelial cells within the glomerular tuft and demonstrate that these cells can act as  
147 podocyte progenitors during kidney development.<sup>8</sup> In further studies, the same authors demonstrated that  
148 parietal epithelial cells represent a major constituents of sclerotic lesions in focal segmental  
149 glomerulosclerosis and, together with podocytes,<sup>29</sup>, in crescents<sup>30,31</sup>. In a more recent article, Berger *et al.*  
150 proposed that committed podocytes are recruited from Bowman's capsule even after birth, and that this  
151 represents a committed intrinsic "podocyte reserve", which can be recruited to allow glomerular growth<sup>32</sup>  
152 and may be particularly active in human<sup>33</sup>. Interestingly, Sagrinati *et al.* had described a progenitor potential of  
153 parietal epithelial cells in human.<sup>34-38</sup> Of note, in human, parietal epithelial cells of the Bowman's capsule  
154 appear as undifferentiated at the urinary pole<sup>38</sup> and as podocyte-committed in more proximity to the vascular  
155 pole<sup>38</sup> and, like putative tubular progenitors, are characterized by co-expression of CD133 and CD24.<sup>34-38</sup>. In  
156 their study, Berger *et al.* assumed that, similarly to CD133, their mouse may tag tubular progenitors in  
157 addition to parietal epithelial cells and then described a lack of amplification of tagged tubular cells  
158 following acute kidney injury.<sup>28</sup> However, at difference with cells expressing CD133 in human kidney, that  
159 were previously reported to behave as progenitors *in vitro* and following their transplantation in models of

160 acute tubular injury *in vivo*,<sup>26,34-41</sup> the scattered tubular cells in the transgenic mouse described by Berger *et*  
161 *al.* were not functionally studied.<sup>28</sup> In this mouse, multiple different cell types in addition to parietal epithelial  
162 cells are tagged, and the progenitor nature of the tagged scattered tubular cells is hypothesized based on  
163 expression of four markers that are shared by CD133+ human renal cells as well as by mouse parietal  
164 epithelial cells of the Bowman's capsule in addition to other cell types. Of note, the distribution of tagged  
165 tubular cells is also different from that reported for the CD133+ human tubular progenitors, that are mostly  
166 localized in the S3 segment and distal tubule,<sup>26,34</sup> while tagged cells in this mouse mostly localize in the  
167 S1+S2, as well as S3 segment.<sup>28</sup> Since it is unknown if tubular progenitors in this mouse are really tagged,  
168 the absence of their amplification in response to injury does not allow to conclude about their existence and  
169 role. Thus, as a general concept, if lineage tracing strategies demonstrate self renewal and differentiation  
170 capacity of the tagged cell population, one can conclude positively on the existence of a progenitor  
171 population. However, if the cell type marked by the promoter is unknown, negative results never allow  
172 definitive conclusions. Thus, the questions if tubular progenitors exist in the mouse and are involved in  
173 tubular regeneration remain open. This further underlines how critical is the choice of the promoter used for  
174 lineage tracing. For all these reasons, to draw conclusions about putative tubular progenitors, models that  
175 exploit physiologically expressed genes at single cell resolutions that are progenitor-specific and which,  
176 consequently, may unify human and mouse studies, are mandatory.

177 In fact, human stem cell studies usually rely on prospective isolation based on specific markers followed by  
178 functional analysis including *in vivo* transplantation assays).<sup>34-41</sup> Accordingly, in the human fetal kidney and  
179 Wilms tumor, Ncam1 and Aldh1 (especially the Aldh1a2 paralogue),<sup>42-47</sup> CD133 and CD24<sup>48</sup> have been put  
180 forward as stem/progenitor cell markers in early mesenchyme (Six2<sup>+</sup>) and derived epithelial precursors (Six2<sup>-</sup>  
181 ).<sup>42-48</sup> In the human adult kidney, CD133, CD24 and Aldh have been suggested to mark putative *in situ*  
182 epithelial progenitor populations while Ncam1 down-regulated after completion of nephrogenesis and  
183 reactivated in culture and following injury,<sup>49</sup> delineated a clonogenic cell subset that exhibited de-  
184 differentiation, epithelial-to-mesenchymal transition characteristics converting to a stem cell-like state.<sup>49</sup>

185 Lineage tracing based on such markers may define a role in tubular homeostasis and regeneration for  
186 progenitors similar to the ones described in human. A prerequisite for this analysis is that a given  
187 marker/promoter would share homology in humans and mice, similar mRNA or protein levels and similar



188 expression domain. This could be relevant to Ncam1/Aldh1a2 and hence generation of conditional  
189 Ncam1/Aldh1a2-CreERT2 mice would clarify a role in development and in adults. In contrast, markers such  
190 as human CD133 cannot be used in the mouse kidney.<sup>50</sup> Indeed, human CD133 was first isolated from  
191 hematopoietic stem cells by a monoclonal antibody recognizing a specific epitope designated as AC133.<sup>51,52</sup>  
192 Once included in the Cluster of Differentiation nomenclature (CD), it was thus classified based on the name  
193 of the epitope (CD133).<sup>51,52</sup> CD133 currently serves as a useful marker for the isolation of many different  
194 types of stem and progenitor cells in adult human tissues, even for clinical purpose.<sup>51,52</sup> However, antibodies  
195 that recognize portions of the human CD133 protein different from the AC133 epitope do not specifically  
196 recognize stem cells, but are rather expressed by many differentiated epithelia.<sup>51,52</sup> Recent results suggest that  
197 only antibodies that recognize epitopes localize in the second extracellular loop, like the AC133 and 293C3  
198 clones used to identify human renal progenitors,<sup>50</sup> are suitable for stem cell and progenitors recognition.<sup>51,52</sup>  
199 Although for these reasons use of CD133 mRNA or gene to detect renal progenitors in the mouse is currently  
200 not possible,<sup>34,50</sup> a lineage tracing approach that uses a promoter that is co-expressed with CD133 on renal  
201 progenitors may be suitable. Future studies are required to address this possibility. Importantly, there may  
202 exist the opposite situation in which a murine marker such as Sca1, previously shown to identify an MSC-  
203 like cell population in the adult mouse kidney),<sup>49</sup> has no homologous protein in humans, precluding  
204 transplantation assays with counterpart human cells. Therefore, for any kind of promoter system used, the  
205 expression pattern has to be accurately chosen and verified prior to the actual cell fate tracing experiments.

206

207 **The switch** The power and specificity of lineage tracing is in the variety of 'switches' that are now available  
208 to allow a temporal control over the activity of the Cre recombinase. Indeed, it must be underlined that the  
209 simple use of a cell-specific promoter that directly drives Cre expression without the use of a switch that  
210 allows turning on and off of Cre recombinase transcription over time, can alter the results obtained with  
211 lineage tracing. Indeed, transient expression of the gene in another cell population, or later expression in cells  
212 of the tissue under study can induce *de novo* activation of Cre recombinase in a way that a part of the newly  
213 generated cells won't be derived from initially tagged ones. This *in vivo* genetic fate mapping is frequently  
214 confused with lineage tracing analysis and cannot give conclusive results, and often leads to over

215 interpretation of the data. For example, Sakamoto et al.<sup>53</sup> concluded, in a model of FSGS, that podocytes  
216 transit into a parietal epithelial cell phenotype<sup>53</sup>. However, in the constitutive mouse model used in this  
217 study, upregulation of podocyte markers may have occurred in whatever moment in parietal epithelial cells  
218 leading to Cre recombinase activation and cell tagging, and thus the labelled cells may also represent parietal  
219 epithelial cells differentiating into podocytes.<sup>53</sup> For this reason, lineage tracing needs to be based on temporal  
220 regulation of marker gene expression. To this aim, inducible models have been created, also termed  
221 conditional models. Cell-specific promoters have been modified with regulatory elements that control Cre  
222 expression only when activated by specific exogenous molecules. As a consequence, the Cre recombinase  
223 will recombine the DNA in the desired cells that express the marker gene, only during the administration of  
224 the inductor molecule, thus opening a transient window in which cells may be labeled. Upon withdrawal of  
225 the molecule, no other cell that has not been labeled during the administration window can undergo genetic  
226 recombination, neither if it express the cell-specific promoter. Conditional assays principally rely on  
227 Tamoxifen-regulated systems (CreER<sup>T</sup>) (**Fig. 1A**) or on Tetracycline-regulated systems (**Fig. 1B**).  
228 Tamoxifen-based systems are built to constitutively express an inactivated form of Cre recombinase fused to  
229 a modified Estrogen Receptor (ER<sup>T</sup>) (**Fig. 1A**). When tamoxifen binds to the ER the protein can modify its  
230 structure and enter the nucleus, gaining access to DNA, where activated Cre may recombine (**Fig. 1A**). In  
231 Tetracycline-controlled systems the cell-specific promoter drives the expression of a reverse tetracycline-  
232 controlled transactivator (rtTA) (**Fig. 1B**). When this protein is ligated by administered Doxycycline, it will  
233 bind DNA sequences of Tetracycline-controlled transcriptional activation-elements (Tet), which in turn  
234 drives Cre expression (**Fig. 1B**). Cre will then act on the reporter transgene by ligating loxP elements (**Fig.**  
235 **1B**). An interesting comparison of how different the result can be when obtained with constitutive versus  
236 conditional mice can be observed in two recent studies by Pippin *et al.*, who used the renin gene as a cell-  
237 specific promoter in order to label and trace cells of the juxtaglomerular apparatus.<sup>54,55</sup> The authors  
238 demonstrated that renin expressing cells have regenerative capacity and are able to replace podocytes as well  
239 as parietal epithelial cells in a mouse model of FSGS, suggesting that they may serve as upstream  
240 mesenchymal progenitors for both parietal epithelial cells and podocytes.<sup>54</sup> In both of these studies, the  
241 authors used a constitutive model in which renin drives the recombination that leads to fluorophore ZsGreen  
242 expression, within cells.<sup>54,55</sup> Using this fate mapping approach, the authors reported an increase in cells of

243 renin lineage in the intraglomerular compartment at 14 days after injury, with a subset that coexpressed the  
244 podocyte markers nephrin, podocin and synaptopodin, indicative of a podocyte-like marker  
245 phenotype.<sup>54</sup> Since any cell population that had expressed renin, in any moment of animal life, would result  
246 as genetically tagged, the use of a constitutive model here, limits our interpretations into whether the renin-  
247 positive population contributes to podocyte replenishment. Moreover podocytes can express renin under  
248 some circumstances, which could be an alternative explanation for the co-expressions of podocyte  
249 markers and fluorescence signal.<sup>56-58</sup> In one of the two studies<sup>54</sup> the authors also used a conditional mouse  
250 system to perform lineage tracing of renin cells, and similarly concluded that these cells can act as podocyte  
251 progenitors.<sup>54</sup> However, when traced with the conditional mouse in the same FSGS model, renin expressing  
252 cells that derived from podocytes appeared to be extremely rare, more than ten fold less than with the  
253 conditional mouse.<sup>54,55</sup> These studies reveal that these methodological aspects can have strong impact on data  
254 interpretation and conceptual conclusions.

255 Interestingly, a recent study by Starke *et al*<sup>9</sup> further analyzed the hypothesis that cells of renin lineage act as  
256 precursors for other renal cells by using an inducible mouse model that labeled renin cells with  $\beta$ -gal.<sup>9</sup> In  
257 that paper, the authors demonstrated that two-thirds of the glomerular tufts became  $\beta$ -gal positive following  
258 mesangial injury and intraglomerular renin descendant cells colocalized only with mesangial but not with  
259 endothelial, podocyte, or parietal epithelial cell markers, suggesting that renin cells can act as precursors for  
260 mesangial cells, but not for podocytes.<sup>9</sup> Thus, further studies are required to effectively address the  
261 contribution of renin cells to podocyte replenishments.

262 Although the use of a time dependent switch is an essential pre-requisite for a correct lineage tracing  
263 experiment, further important caveats should be considered when designing such an experiment and  
264 interpreting results. First of all, it has to be considered that the doses of the drug given to the animal will  
265 affect the analysis, and thus must be chosen depending on the experimental purpose. Indeed, low or sub-  
266 optimal administration will label the population of interest at clonal density, and it is therefore used to study  
267 origins of particular cell population, as demonstrated by Rios *et al*.<sup>3</sup> High doses will instead maximize the  
268 labeling of the entire stem/progenitor pool, enabling the visualization of their cumulative contributions  
269 within the entire compartment.<sup>13,14</sup> Second, an important limitation for conditional experiments can be  
270 leakiness of the system: where there is residual recombination even in the absence of induction. Because of

271 this limitation, multiple control groups must be estimated in all experimental conditions, and various tissues  
272 must be evaluated. Additional limitations include, transgene constructs that may spontaneously silence and  
273 lead to under representation of data. Cell fusion events may also occur *in vivo* in a number of tissues<sup>59</sup> leading  
274 to spreading of fluorophore expression, and to false interpretations of multi-lineage contributions.<sup>13,14,60</sup> Third,  
275 it must be considered that drugs like tamoxifen or doxycycline can be given through different routes of  
276 administration, like intraperitoneally, by chow or drinking water, introducing a variability in results,  
277 depending on timing, health conditions, age, weight, and more. Finally, mosaic activation of cre  
278 recombination can occur. Indeed, ideally, the reporter gene is driven by a ubiquitously active promoter or  
279 gene locus. Unfortunately, no such promoter has been identified so far. Viral promoter fragments usually are  
280 transcriptionally active in a mosaic fashion, and the ROSA26 locus is transcriptionally active at a low level  
281 in most cells but it may be transiently down-regulated in diseased tissue."  
282 All these considerations, highlight how challenging lineage tracing experiments can be, and how an accurate  
283 choice of the switch and of its timing, are critical determinants of the results and of their interpretations.

284

285 ***The reporter*** The third critical ingredient for a lineage tracing experiment is the choice of the reporter.  
286 Traditionally, the *Escherichia coli* lacZ gene,  $\beta$ -galactosidase, was one of the first reporters used for lineage  
287 tracing and has been used extensively.<sup>13,14</sup>  $\beta$ -galactosidase produces an intense blue color when incubated  
288 with the substrate analog X-gal, but is technically difficult and can be variable. Alternatively, beta-gal can be  
289 visualized using immunofluorescent stainings, although with such methods podocytes may show low-level  
290 background staining.<sup>13-15</sup> Fluorescent reporters have become the new standard, and in this case detection by  
291 epifluorescence is far superior to antibody-enhanced methods, which are subject to nonspecific binding of  
292 antibodies and also raises the possibility of imaging clones of cells in living tissue through the use of  
293 multicolor reporters. Such dynamic analysis of cell-fate decisions is facilitated by advances in imaging, such  
294 as two- or multiphoton fluorescence microscopes, which enable in-depth scanning and optimal fluorophore  
295 separation of the multicolor fluorescence, as recently illustrated by an elegant study that used this approach  
296 to visualize podocyte response to injury.<sup>61</sup> In multicolor reporters, attention should be paid to the use of lines  
297 that express Cre constitutively because a change in cell color ("flipping") may occurs even after the initial  
298 Cre recombination. Therefore, multicolor reporters are optimal when used in combination with inducible Cre

models. The high choice of different reporters that are becoming available is now one of the major strengths of lineage tracing approaches, but can also limit comparisons of results and their interpretations. For instance, the sensitivity to Cre-mediated recombination of different reporter alleles targeted to the *Rosa26* locus can vary substantially. Some *Rosa26*-targeted reporters will respond efficiently to Cre but can show leaky expression (background expression) in the absence of the Cre-inducing drug.<sup>13-15</sup> Others are less efficient, and so have less background.<sup>13-15</sup> These issues are crucial when comparing studies in which Cre is being used to report gene expression or signaling activity, as the proportion of cells labeled may reflect the reporter that is used as much as the level of Cre activity.<sup>13-15</sup> However, a careful choice of the reporter may even allow sophisticated quantitation of regeneration after injury processes. To this aim, one of the most used reporter genes is the *mT/mG(membraneTomato/membraneGreen)* transgene, which is characterized by a constitutive expression of the membrane bound fluorescent Tomato Red protein in all the cells of the animal body (**Fig. 2A**). As the sequence encoding the Tomato Red is floxed by two loxP site, only cells that will undergo recombination events will be able to express the membrane bound GFP which is downstream of Tomato Red, thus turning red into green (**Fig. 2A**). One example of a paper which used this system is Wanner *et al.* that studied podocyte turnover and regeneration in aging, in a unilateral nephrectomy models and following acute podocyte loss.<sup>62</sup> To study severe podocytes depletion the authors employed a quadruple transgenic model in which the podocyte marker Podocin conditionally induced the shift of the *mT/mG* transgene present on one *Rosa26* allele, while inducing the expression of the human simian Diphtheria toxin receptor (iDTR) transgene, codified under the other *Rosa26* allele (**Fig.2**).<sup>62</sup> Using this methodology, podocytes were tagged in green and were induced to express the iDTR following doxycycline administration, making them susceptible to a specific ablation as a consequence of the Diphtheria toxin injection.<sup>62</sup> With this approach, newly generated podocytes can only be red colored due to the withdrawal of doxycycline before the onset of the damage.<sup>62</sup> While this approach enables quantification of *de novo* generated podocytes, it does not permit to identify the source of the novel podocytes population, neither does it allow to establish the origins or identities of the progenitor population.<sup>62</sup> By employing this transgenic mouse model the authors reported, at 4 week from Diphtheria toxin (DTA) injection, a significant increase in the percentage of red-positive (newly generated) podocytes after ablation (**Fig. 2B**), corresponding to regeneration of 38% of lost podocytes, while after nephrectomy and in an aging model no increase in

327 Tomato Red<sup>+</sup>podocytes was reported.<sup>62</sup> Interestingly, the DTA model is the only one that is characterized by  
328 podocyte depletion, while nephrectomy and aging do not necessarily lead to podocyte loss. This suggests that  
329 podocyte regeneration may occur only after podocyte detachment or death.

330 Even if genetically modified mice with inducible recombination under different promoters have been used  
331 for *in vivo* fate mapping in the kidney, these analyses were performed on the population level, and not on  
332 individual cells. As such, cellular models for kidney development, physiologic tissue maintenance, and  
333 regeneration *in vivo* remained open questions. To this aim, multicolour reporters, that enable combinatorial  
334 expression of multiple fluorescent proteins in a stochastic manner under the control of a specific  
335 promoter, like the 'Brainbow' (**Fig. 3**), 'Rainbow' or 'Confetti' constructs, have opened a new wide range of  
336 possibilities.

337 Rinkevich *and* Dekel.,<sup>12</sup> have recently utilized such a genetic marking strategy for lineage tracing of  
338 individual renal precursors in the adult mouse kidney. This strategy entails the use of a multicolor (red,  
339 yellow, green, blue) Cre-dependent reporter construct within the ROSA locus ( $R26^{VT2/GK3}$ , termed  
340 'Rainbow'), in addition to a lineage tracing strategy that is independent of candidate markers (using an  
341 inducible Cre-ER fusion protein under the ubiquitous Actin promoter).  $Actin^{CreER}$ ;  $R26^{VT2/GK3}$  offspring  
342 injected with tamoxifen, induced cytoplasmic fusion protein to enter the nucleus and permanently recombine  
343 a random single color-encoding gene in all renal epithelial cells, regardless of their locations, marker gene  
344 expressions or developmental potentials.<sup>12</sup> Using this unbiased assay, clonal analysis of individual cells over  
345 a 7-month period was performed, revealing the emergences of unipotent clones of three major types  
346 (proximal, distal tubule, and collecting tubules) each of which contributed to individual tubule segments over  
347 that tracing period<sup>12</sup> (**Fig. 4A**). Because of the cellular density of the kidney tissue, clonal analysis using a 4-  
348 color reporter construct may mask cellular contributions from adjacent and similarly colored cells to these  
349 clones.<sup>12</sup> To circumvent this possibility, Rinkevich *and* Dekel., have employed a protocol using single and  
350 low doses of tamoxifen. In these experiments, the tissue frequency of recombination was low enough (<1%)  
351 as to sparsely label single cells with individual fluorescent colors within large and non-colored kidney  
352 domains.<sup>12</sup> These low-dose experiments demonstrated that large and single colored clones are outputs of  
353 individual cells that generate and regenerate the kidney epithelia<sup>12</sup> (**Fig. 4B, white arrows**). Thus, using a  
354 ubiquitous, unbiased promoter (Actin), clonal analysis helped identify a distinct mode of renal epithelial cell

turnover in maintenance and following ischemia and toxic AKI.<sup>12</sup> Long-term lineage tracing *in vivo* revealed significant tubulogenesis has occurred within the mature kidney epithelia that produce slowly expanding clonal foci with segmental boundaries. To visualize the full sizes and distributions of clones Rinkevich and Dekel isolated intact nephron segments from *Actin*<sup>CreER</sup>; *R26*<sup>VT2/GK3</sup> mice that were chased for 7-months<sup>12</sup> (**Fig. 4, C, D**). Intact tubules exhibited large epithelial clones within individual segments indicating that cells with lineage-restricted capacities and progenitor characteristics reside within tubule segments of the nephron.<sup>12</sup> Following this 7-month clonal analysis, large clones also appeared within multiple glomeruli (**Fig. 4, E-G**), indicating that both adult tubules and glomeruli house active clone forming cells.<sup>12</sup>

Another system that is employed for lineage tracing and clonal analysis during embryonic development involves the creation of multicolored chimeric mice, termed tetrachimera mice.<sup>63</sup> These mice are generated by injecting mouse embryonic stem cells that express separate fluorescent proteins (GFP-mES, RFP-mES, CFP-mES) into wild-type blastocysts.<sup>63</sup> Kidneys from generated tetrachimera mice revealed that mature nephrons were polyclonal, indicating derivation during development from mixed contributions of clones, each of which contributed to individual tubule segments and to individual regions within nephrons<sup>63</sup> (**Fig. 4H**).

Clonal analysis can further be used in the context of generating renal organoids. Following our previous success in establishing long-term kidney sphere cultures from single cell suspensions of human patients, recapitulating renal features and *in vivo* renal capacity,<sup>42,64</sup> Rinkevich et al.<sup>12</sup> recently used the Rainbow system to investigate the *in vitro* fates from individual renal precursors, by establishing a culture system of growing murine renal epithelial organoids in suspension.<sup>12</sup> In this assay, kidneys were harvested from *Actin*<sup>CreER</sup>; *R26*<sup>VT2/GK3</sup> mice immediately after a tamoxifen administration regimen, dissociated into single cells, and plated with matrigel. Within several days of culturing, monoclonal renal organoids developed from individual cells that gradually enlarged, and then opened into hollow spheres resembling renal tubes *in vivo*.<sup>12</sup> Similar to *in vivo* observations, clonal progeny developing within renal organoids maintained segment identity. When combined with isolation of renal cell fractions using flow cytometry, This type of approach allows the identifications of *in vitro* clonal efficiencies as well as progenitor frequencies within isolated FACS-sorted renal fractions<sup>12</sup> (**Fig. 4, I-I''**).

382 The same study also examined the clonal capacities of Wnt-responsive cells by using a Wnt reporter  
383 *Axin*<sup>CreER</sup> that expresses the Cre-ER fusion protein under the promoter of the *Axin* gene; which provides  
384 negative feedback in the Wnt- $\beta$ -catenin signaling pathway. Single cell analysis was performed on the  
385 population of renal cells that were Wnt responsive by crossing *Axin2*<sup>CreER</sup> mice to 'Rainbow' reporter  
386 mice.<sup>12</sup> *Axin2*<sup>CreER</sup>; *R26*<sup>VT2/GK3</sup> that were lineage traced from e17.5 up to the 5<sup>th</sup> postnatal months showed  
387 single colored and large clones within the adult tubules, indicating that they derived from individual Wnt-  
388 responsive precursors<sup>12</sup> (**Fig. 4J**). The authors performed a comparison of clone size between the unbiased  
389 clonal analysis (*Actin*<sup>CreER</sup> promoter) and clonal analysis using Wnt-responsive cell fractions  
390 (*Axin*<sup>CreER</sup> promoter).<sup>12</sup> Their analysis suggests that Wnt-responsive cells (WRCs) are cells with significant  
391 proliferative capacity, behaving *de facto* as long-lived unipotent progenitors when an appropriate stimuli to  
392 clonally expand/self-renew is received.<sup>12</sup>

393 Consistent with this, Barker *et al*<sup>7</sup> has identified cells within developing kidney (following epithelial  
394 induction) that express LGR5<sup>+</sup> (a Wnt co-receptor). The authors crossed *LGR5*<sup>CreER</sup> with a similar multicolor  
395 (red, yellow, green, blue) Cre-dependent reporter construct within the ROSA locus (the Confetti reporter)  
396 and found individual LGR5<sup>+</sup> cells (most likely Wnt responsive cells) as the immediate progenitors that  
397 generate the thick ascending limb of Henle's loop and distal convoluted tubule.<sup>7</sup> Despite the fact that LGR5 is  
398 silenced at postnatal stages of development and fails to trace Wnt-responsive cells in the adult, both reports  
399 demonstrate that constant tubulogenesis is occurring within the mammalian kidney via a similar mechanism  
400 involving Wnt-responsive precursors giving rise to other cells.

401 Taken altogether, the *in vivo* clonal analysis demonstrates that lineage-committed cells with progenitor  
402 characteristics continuously maintain and self-preserve the mouse kidney throughout life and after AKI.

403

404 **An outlook on emerging methodologies** In the most recent years, novel techniques emerged that can  
405 potentially solve many of the ongoing questions and debates about kidney regeneration. The recent  
406 observation that adult progenitors expressing low levels of differentiation markers may be involved in  
407 regeneration of adult tissues was for example recently addressed in the brain by using Split-cre. Such a  
408 strategy, which can allow lineage tracing of a specific population in response to a combination of two



409 reporters, can be achieved by expressing the two fragments of a split Cre recombinase from two different  
410 tissue-specific promoters.<sup>65,66</sup> This lead to the characterization of different types of progenitors in adult  
411 mouse brain based on co-expression of CD133 and neural-specific markers.<sup>22-24,67</sup> Fate mapping experiments  
412 based on the overlapping activity of two promoters can also be performed by using two independent  
413 recombinases (Cre and Flp) driven by two promoters combined with a special reporter allele.<sup>67</sup> This system  
414 has been used to identify and analyse neural progenitors in several brain regions.<sup>23,24,68</sup> These strategies may  
415 be applied also to address the existence and potential role of renal progenitors in the mouse kidney.

416 Although lineage tracing techniques hold the potential to change our knowledge of kidney biology, they add  
417 to their complexity being time consuming and highly costly. Indeed, genetic manipulation in mammalian  
418 species are usually made in the germline of an organism, which can then be used to create a stable transgenic  
419 strain for experimentation.<sup>69</sup> Recently, however, the RNA-guided endonuclease Cas9 from microbial type II  
420 CRISPR (clustered regularly interspaced short palindromic repeat) systems (previously referred to as Cas5 or  
421 Csn1)<sup>70-78</sup> has been harnessed to facilitate genetic manipulations in a variety of cell types and organisms  
422 (reviewed in Hsu et al., 2014).<sup>77</sup> A major advantage in CRISPR/Cas gene editing is that reactions can be  
423 multiplexed to introduce multiple genome modifications in a single step.<sup>77,78</sup> Cas9 can be easily  
424 reprogrammed using RNA guides to generate targeted DNA double-strand breaks (DSBs), which can  
425 stimulate genome editing via one of the two DNA damage repair pathways: nonhomologous end-joining  
426 (NHEJ), resulting in insertions and deletions (indels) or homology-directed repair (HDR), resulting in precise  
427 sequence substitution in the presence of a repair template.<sup>77,78</sup> Unlike other programmable nuclease systems  
428 used for genome editing, a unique advantage of the Cas9 system is that Cas9 can be combined with multiple  
429 single-guide RNAs (sgRNA). However, commonly used delivery systems based on lentiviral and adeno-  
430 associated viral (AAV) vectors have limited packaging capacity which renders it challenging for  
431 incorporation of Cas9 along with sgRNA expression cassettes and necessary genetic elements (i.e.,  
432 promoters, fluorescent proteins, and polyadenylation sequences). Thus, to facilitate broader applications of  
433 CRISPR-Cas9, Platt et al. generated a Cre-dependent Rosa26 Cas9 knockin mouse to overcome the delivery  
434 challenges associated with Cas9 (**Fig. 5**).<sup>79</sup> Cas9-expressing cells derived from the constitutive Cas9-  
435 expressing mice facilitate genome editing because it requires only the introduction of sgRNAs, which can be  
436 efficiently delivered using viral and nonviral sgRNA delivery methods.<sup>79</sup> This mouse can be used in

437 conjunction with a variety of guide RNA delivery reagents, including to facilitate genome editing in multiple  
438 tissues *in vivo* (**Fig. 5**).<sup>79</sup> *In vivo* as well as *ex vivo* genome editing using adeno-associated virus (AAV)-,  
439 lentivirus-, or particle-mediated delivery of guide RNA in neurons, immune cells, and endothelial cells was  
440 reported.<sup>79</sup> More importantly, Platt et al. delivered a single AAV vector in the Cre-dependent LSL-Cas9  
441 model to generate loss-of-function mutations in the tumor suppressors *Trp53* (*p53*) and *Lkb1*, and homology-  
442 directed repair modification of *Kras* to oncogenic *KrasG12D* simultaneously.<sup>79</sup> Intra-tracheal delivery of this  
443 vector, which also carried Cre and a luciferase reporter sequence in addition to the sgRNA and *KrasG12D*  
444 homology repair templates, resulted in adenocarcinomas in 100% of the infected animals.<sup>79</sup> These data  
445 suggest that the conditional LSL-Cas9 mice provide exciting new tools to perform targeted genomic  
446 manipulation in traditionally challenging cell types *in vivo* and *ex vivo*, and to generate novel and fast  
447 strategies for lineage tracing which hold great promises for regenerative studies.

448

## 449 **Conclusion**

450 Lineage tracing strategies are powerful tools that are now growingly applied to understand the physio-  
451 pathological mechanisms that govern kidney regeneration and disease. Novel options to enhance the system  
452 and its possible applications are continuously becoming available, further increasing its possible  
453 applications. Caution must be paid particularly to the type of promoter, switch and reporter used, as well as  
454 on the induction times that are best to study the pre-specified end points. Even with these caveats, lineage  
455 tracing strategies are making accessible to our knowledge a wide range of processes, including kidney  
456 regeneration, which can now be directly visualized for the first time. Lineage tracing methods at single cell  
457 resolutions rather than cell populations would provide the most accurate genealogical descriptions of  
458 stem/progenitor behaviors. Consequently, novel types of murine models where renal progenitors are  
459 specifically tagged are being produced, and novel techniques to reduce the complexity and costs of lineage  
460 tracing experiments are appearing. Gradually, mechanisms of kidney regeneration are being clarified and new  
461 answers to old questions are gradually being found. These approaches and their use will allow the  
462 identifications and complete characterizing of all progenitor populations within the kidney and their  
463 contribution to kidney regeneration with unprecedented resolution and accuracy.

464

465

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470

471     **Competing interests**

472     Paola Romagnani is author of two patents on human renal progenitors (patent numbers: PCT/EP2007/054132  
473     and F12013A000303) that are property of the University of Florence as well as of the public paediatric  
474     Meyer Children's Hospital.

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## LEGEND FOR FIGURES

**Figure 1 Cre-recombinase-based lineage tracing system.** Schematic representation of two of the most common strategies used for lineage tracing. The genetic background of one animal is altered such that a specific promoter is used to induce Cre recombination in specific cells. These mice are crossed to a reporter animal harbouring a stop codon flanked by Cre-recombinogenic *loxP* sites upstream of a reporter gene, such as *lacZ* or *GFP*, under the control of the *Rosa26* promoter. In mice expressing both genetic elements, Cre recombinase excises the stop codon, such that *Rosa26* drives expression of the reporter in stem cells. Once marked in this way, all descendants propagate the expression of the reporter under *Rosa26* promoter control. In Cre recombinase expression can be activated at defined time-points through treatment with specific drugs.

(A) Temporal restriction can be achieved by fusing the Cre recombinase gene to the tamoxifen-responsive hormone-binding domain of the estrogen receptor (Cre-ER<sup>TAM</sup>). The Cre enzyme is in an inactive state in the absence of the ligand tamoxifen. Once tamoxifen is added, the Cre is active and can translocate to the nucleus. In the absence of tamoxifen, no expression of the reporter gene is observed because of the presence of the stop signal upstream of the reporter gene. When tamoxifen is administered, the Cre is activated and mediates recombination between the *loxP* sites in cells. As a consequence, the STOP codon is excised and the cells are permanently marked by the reporter gene. ER, estrogen receptor; GFP, green fluorescent protein.

(B) Tet-on strategy for inducible and temporal control of transgene expression is based on the tetracycline (tet) bacterial resistance gene operon. Three transgenic lines are required. The first transgenic line contains the tTA under the control of a cell-specific promoter: this line provides the selectivity to the system. The second transgenic line contains the transgene of interest under the control of the tet operon (TetO) DNA-binding element. The TetO promoter element can be activated upon binding of the tetracycline transactivator (tTA) to drive ubiquitous expression. The third transgenic line contains the reporter system. When a tetracycline derivative, such as doxycycline, is given to the trigenic mice (obtained from breeding the tTA line with the TetO line, and then with the reporter line) in the drinking water, doxycycline binds to tTA to induce its interaction with the TetO minimal promoter and thereby turns on transgene expression selectively in the desired cell type.

678 **Figure 2 *mT/mG* Cre-recombinase-mediated reporter for lineage tracing in the kidney.**

679 (A) *mT/mG* is a double-fluorescent Cre reporter construct that expresses membrane-targeted tandem dimer  
680 Tomato (*mT*) prior to Cre-mediated excision and membrane-targeted green fluorescent protein (*mG*) after  
681 excision. Tomato reporter expression is nearly ubiquitous, allowing visualization of fluorescent markers in  
682 live and fixed samples of all tissues examine, while *mG* labeling is Cre-dependent, complementary to *mT* at  
683 single cell resolution, and distinguishable by fluorescence-activated cell sorting. Both membrane-targeted  
684 markers outline cell morphology, highlight membrane structures, and permit visualization of fine cellular  
685 processes, and thus are ideal to study podocytes. (B) *mT/mG* image of an  
686 *hNPHS2.rtTA;TetO.Cre;mT/mG;iDTR* kidney previously induced with doxycycline, treated with DT as  
687 previously reported<sup>49</sup> and compared with healthy controls. After staining with synaptopodin (blue), this model  
688 allows visualization of resident podocytes (green and blue), and of *de novo* generated podocytes (red and  
689 blue) after podocyte injury. Left: A healthy glomerulus, where all resident podocytes appear as green and  
690 blue after doxycycline induction of Cre recombinase activation. Right: After doxycycline washout, induction  
691 of podocyte injury with *iDTR* treatment is followed after one month by generation of novel podocytes that  
692 are not derived from resident podocytes, as demonstrated by the lack of green signal. Newly generated  
693 podocytes appear as synaptopodin positive cells (blue) that are red labelled, showing they were generated  
694 from an external progenitor.

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696 **Figure 3: MulticolourCre-recombinase-mediated reporter for lineage tracing and clonal analysis.**

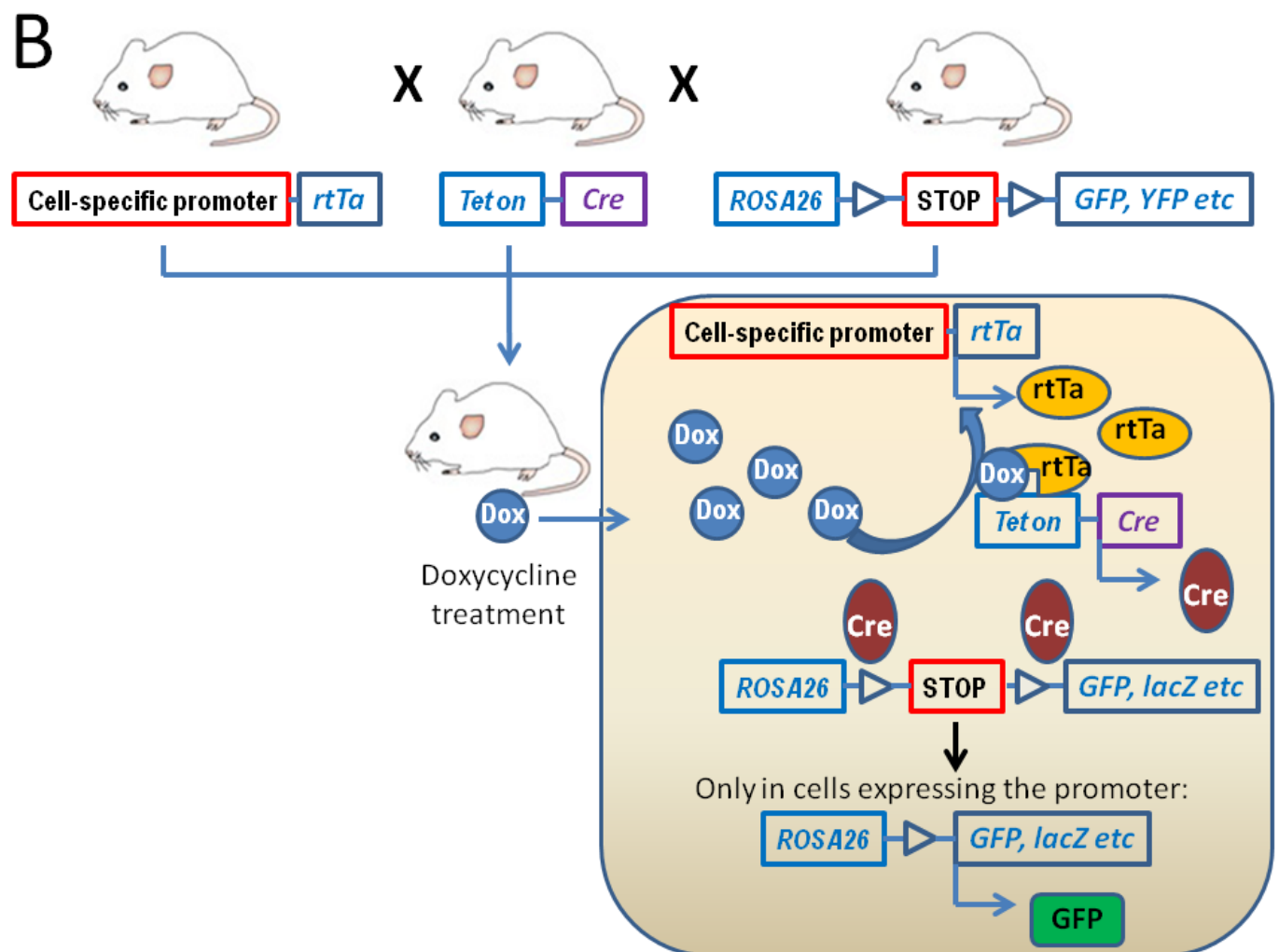
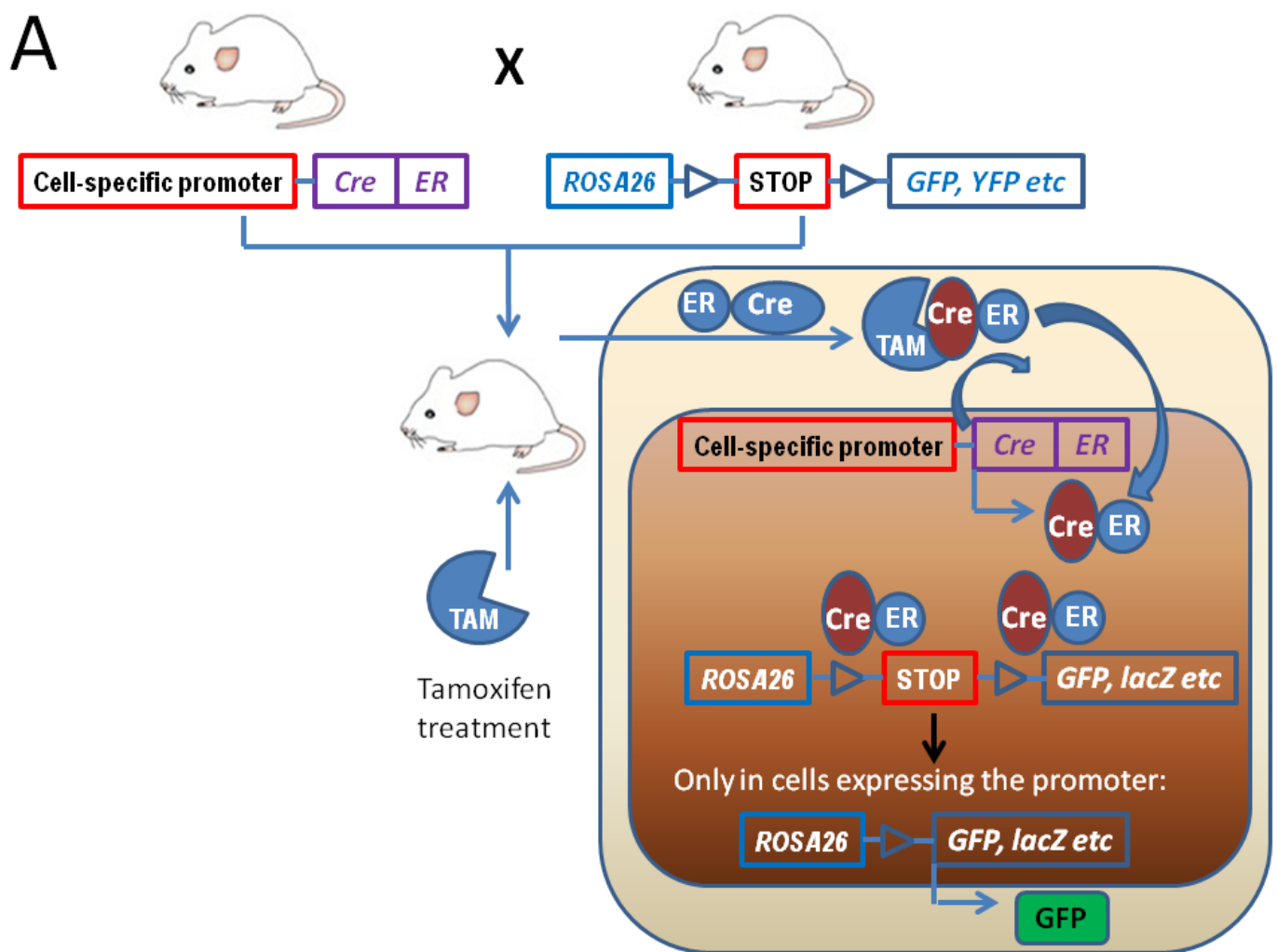
697 (A) Schematic representation of the genetic strategy to mark cells with multiple fluorescent proteins. One  
698 animal harbours a transgene encoding a cell-specific promoter driving Cre recombinase expression. These  
699 mice are crossed to a reporter animal that, under the control of the ubiquitous *Rosa26* promoter, harbour a  
700 neomycin resistance gene flanked by Cre-recombinogenic *loxP* sites, and multiple genes, in sense and  
701 antisense orientations, encoding the fluorescent proteins, GFP, RFP, YFP and CFP (green, red, yellow and  
702 cyan fluorescent protein, respectively) that are flanked by Cre-recombinogenic *loxP* and inversion sites. Cre  
703 recombinase stochastically excises and inverts at the *loxP* sites to generate the possible transgenes shown,  
704 and allow *Rosa26* to drive expression of multiple combinations of fluorescent proteins in cells and their  
705 progeny.

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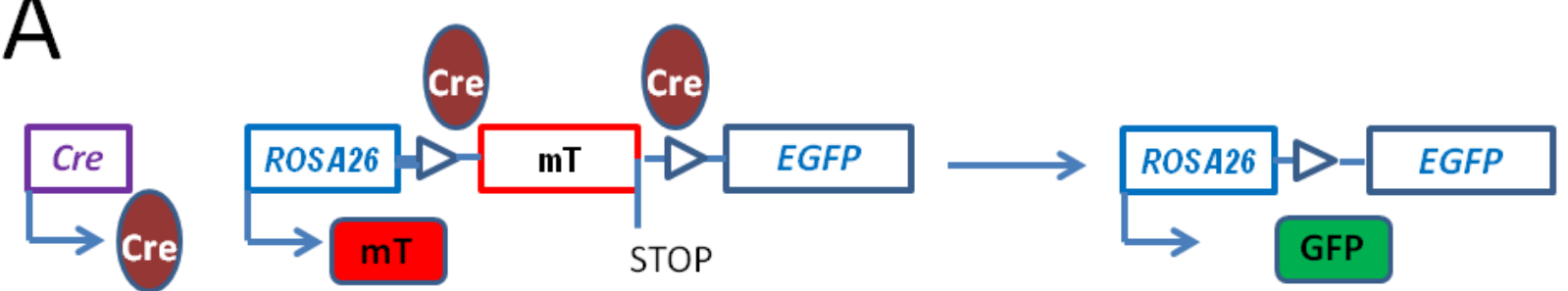
**Figure 4. Clonal analysis of the renal epithelia.**

(A) Merged Rainbow image showing single colored clones within the adult kidney following a 7-month chase in *Actin*<sup>CreER</sup>; *R26*<sup>VT2/GK3</sup> mice. (B) Merged DAPI and Rainbow image showing outcomes of clonal analysis following low dose tamoxifen administration. Large and separate single colored clones are visible within tubule segments. (C, D) Intact nephrons isolated from kidneys of *Actin*<sup>CreER</sup>; *R26*<sup>VT2/GK3</sup> mice indicate that significant tubulogenesis has occurred within adult nephrons. (E-G) Merged Rainbow images of glomeruli showing single colored clones. (H) Merged tetrachimera image of a developing kidney. A large red clone contributing to a nephron segment. (I-I'') Merged images of monoclonal renal organoids following clonal analysis in-vitro. (J) A large single colored clone emerges from a Wnt-responsive precursor, as observed by clonal analysis in *Axin*<sup>CreER</sup>; *R26*<sup>VT2/GK3</sup> mice.

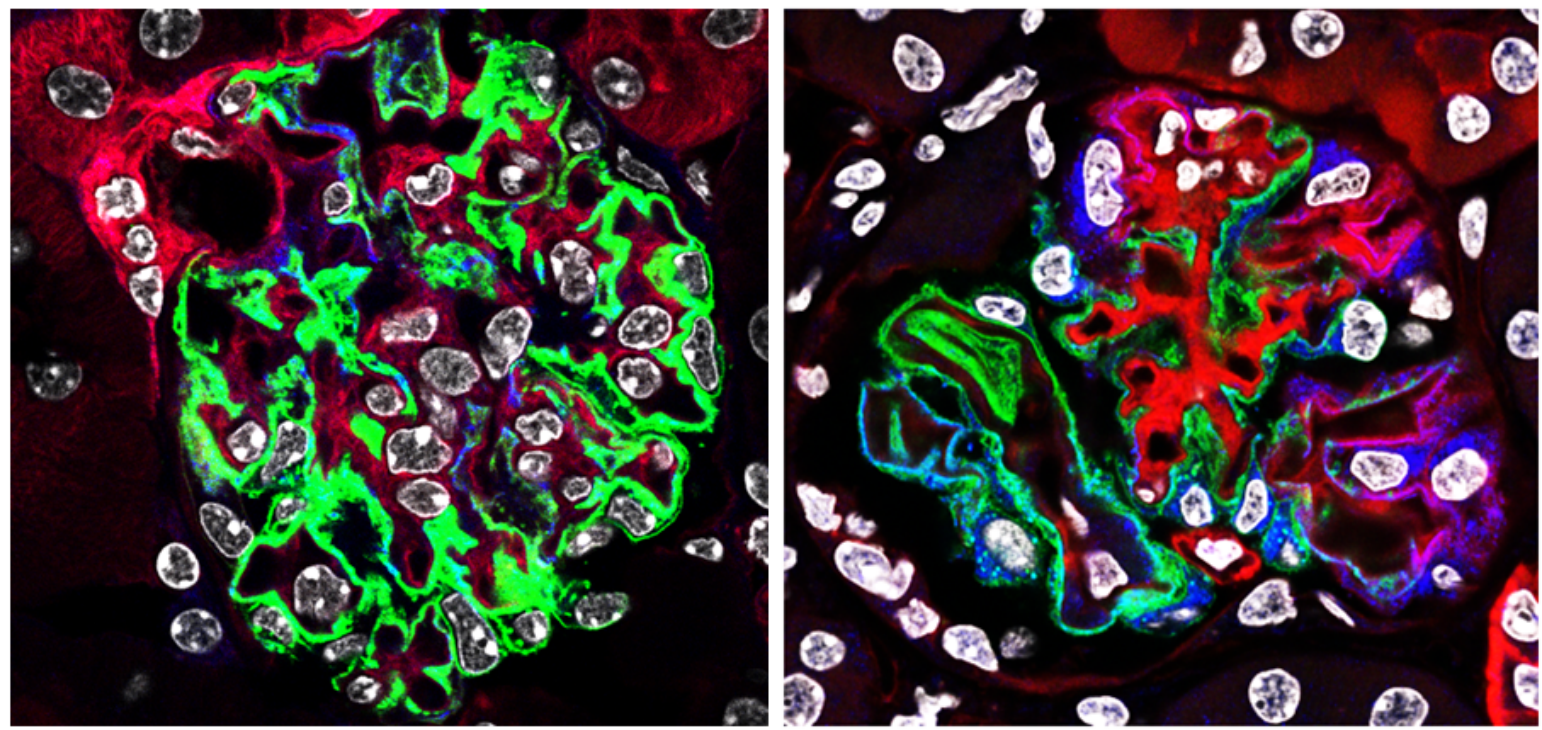
**Figure 5 CRISP-based systems for lineage tracing. Generation of a CRISP-based mouse was recently achieved based on Rosa26-LSL-Cas9 knockin mice** have a floxed-STOP cassette preventing expression of the downstream bicistronic sequences (Cas9 and EGFP). Although under control of a CAG promoter, widespread expression of cas9 and EGFP is prevented by the STOP cassette. After exposure to Cre recombinase, expression of cas9 and EGFP is observed. Cas9 expression is tightly controlled in a Cre-dependent manner, whereas gene editing via viral delivery of cas9 is burdened by packaging size limits. These Rosa26-LSL-Cas9 mice only require one to select a Cre recombinase driven by the promoter of their choosing and a specific single guide RNA (sgRNA) for generating single or multiple simultaneous mutations editing because it requires only the introduction of sgRNAs, which can be efficiently delivered using lentiviral vectors.

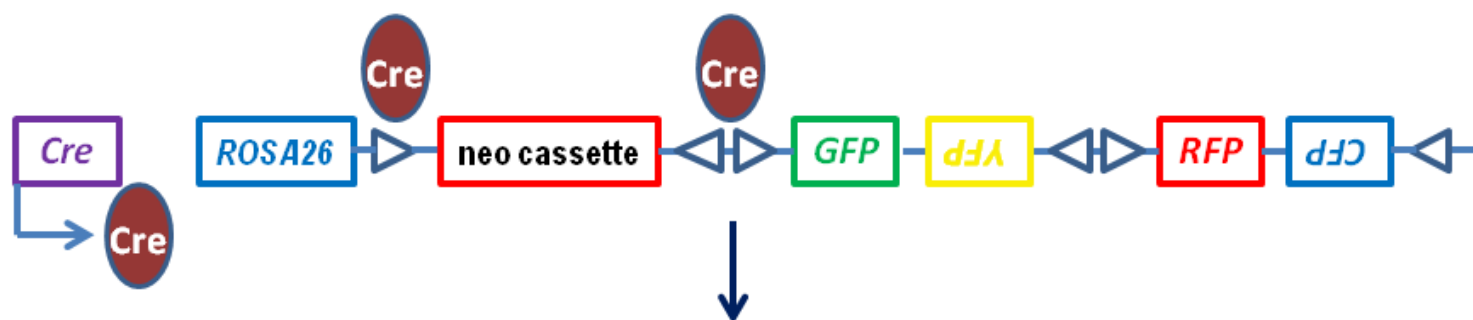


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Stochastic possibilities after Cre recombination:

